FULL-SCALE HDR BLOWDOWN EXPERIMENTS AS A TOOL FOR INVESTIGATING DYNAMIC FLUID-STRUCTURAL COUPLING

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SUMMARY

As an answer to rigorous safety requirements in reactor technology an experimental-theoretical program has been established to investigate safety-relevant mechanical aspects of LWR-blowdown accidents. Part of the program are several full-scale blowdown experiments which will be performed in the former HDR-reactor. As the conceptional study confirms, the primary goal is to find out, how big the safety margins of present LWR's in the case of a blowdown actually are, rather than simply to show that essentional parts of the reactor will withstand such an accident. (This later question is already answered satisfactorily by the state-of-the-art design and computational methods.) However, to determine the safety margins, the physical phenomena involved in the blowdown process must be understood and appropriate ways of description must be found. Therefore the experimental program is accompanied by the development of theoretical models and computer codes. Studies carried through so far indicate, that the dynamic coupling between the expanding coolant and the deforming core barrel within a time region, where the coolant remains in the liquid phase, presents the key problem. Consequently, design of the full-scale blowdown experiments is done in such a way as to give information on this subject of (three-dimensional) fluid structural coupling, rather than giving informations on structural details which are unessential for the overall problem and which may change from one reactor type to another. This led to experimental features which in some cases may be in contrast to real reactor design.

Some of the most important features will be described:

— A core barrel wall thickness of 23 mm. As extensive considerations confirm, it seems to be likely that under this condition the full elastic load carrying capacity of the core barrel can be utilized. In comparison, applying state-of-the-art methods which are shown to be relatively conservative would require a wall thickness of 30 mm.
— An almost rigid core barrel clamping having a residual flexibility of less than 0.2 mm when the full blowdown load is applied.
— An extensive axial and circumferential instrumentation of the core barrel and downcomer including about 170 fast transducers for measurement of absolute and differential pressures, temperatures, displacements, accelerations and strains.
— A well balanced system of heating and cooling circuits to establish stable and predictable temperature differences between the downcomer and the upper plenum. Calculations show that a temperature difference of 50°C can be achieved.

A survey will be given over existing methods for coupled fluid structural dynamics. We will use the following approaches:

— Coupling of an existing finite difference-code for 2D compressible fluid flow (modified YAQUI) with a code for shell dynamics based on modal superposition. First results obtained with a simplified axisymmetric load case show two distinct oscillation phenomena in addition to those obtained for a rigid structure.
— Specific finite difference-code for integrated treatment of both fluid and structure in 3D-geometry using the fast cyclic reduction scheme for solving Poisson's equation.
— Modification of mass and stiffness matrices of FEM-models for shell dynamics by reducing the 3D incompressible fluid problem to 2D with the boundary integral equation method. This presently developed method has the capacity to deal with general problems in fluid-structural coupling.

1. Safety Analysis for PWR Internals under Blowdown Loading Using the State-of-the-Art Approach

In comparison with usual safety analysis in structural mechanics, the proof of the mechanical integrity of the reactor internals within the first tenths of a second of a sudden blowdown is faced with one basic difficulty. The loadings of the structural members, i.e. the transient pressure distributions due to the fluid dynamic processes of the blowdown, cannot be given without taking into account the dynamic response of the structure. Rather the dynamic response changes the boundaries for the fluid dynamic processes and hence influences the resulting transient pressure distributions. These influences become relatively strong even in cases with relatively small boundary deflections, if on one hand the fluid is almost incompressible (small deformations cause large pressure changes) and if on the other hand large amounts of fluid mass (which depend on the fluid density, geometry and compressibility) undergo high accelarations. In other words, as long as the fluid remains in the liquid phase, there may be a strong feedback of the structural deformations on the fluid dynamics. This applies especially to the dynamic behavior of a PWR-core barrel which is believed to be the most critical structural member with respect to blowdown loading. Consequently this paper concentrates on the blowdown response of a PWR-core barrel.

Let us first summarize the state-of-the-art approach, where the feedback of the structural deformations on the fluid dynamics is ignored:
First a fluid dynamic analysis of the blowdown process is performed with a detailed description of the flow inside the downcomer. Since structural deformations due to pressure changes in the fluid are not taken into account, the fluid within the downcomer can be treated as a thin fluid layer having a constant thickness. This means that - as far as the downcomer is concerned - the blowdown process can be approximated by a two-dimensional plane problem of pressure wave propagation. The fluid dynamic inside the core barrel as well as in the lower and upper plenum presents a three-dimensional problem. Also, in these regions variations in geometry due to pressure changes are not taken into account. Furthermore the influence of the core structure on the wave propagation - e.g. the influence of the fuel elements - is usually neglected.
From these simplifications it follows that in case of a blowdown first a zone of reduced pressure occurs in a small portion of the downcomer which is close to the blowdown nozzle (Fig. 1a). Then this zone grows with the velocity of sound in axial and circumferential direction (see Fig. 1b and 1c). In contrast to the impression of these figures there is by no means a step reduction in pressure at the so-called wave front, but rather a very smooth transition. Finally the expansion wave is reflected in the lower plenum, enters the space inside the core barrel and generates an upward moving almost axisymmetric pressure reduction (Fig. 1d).
In a second step the dynamic response of the core barrel is calculated. According to the sequence of pressure reduction, first a small zone of local bending towards the blowdown nozzle occurs (Fig. 1a). With the growth of this zone the local bending transforms into a global bending moment which deforms the core barrel like a beam clamped at the upper end (Fig. 1b). When the zone of pressure reduction has spread over the entire circumference

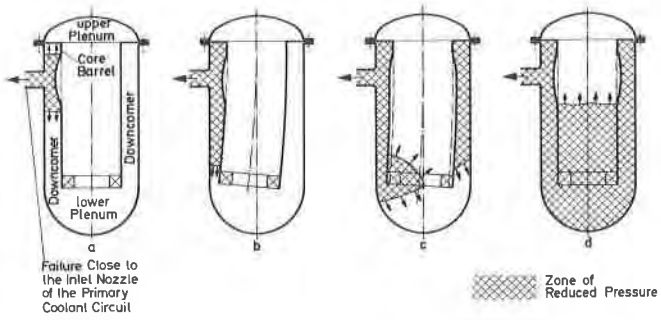


Fig. 1: Expansion Wave Propagation and Growth of Core Barrel Deformations

an almost axisymmetric diameter increase takes place while the global bending moment reduces (Fig. 1c). Then, starting at the lower end of the core barrel also the axisymmetric diameter increase reduces, as the pressure expansion wave travels upward inside the core barrel (Fig. 1d). Although most of the pressure differences are quickly decreasing, the core barrel still oscillates according to the free vibration modes of a thin cylindrical shell, clamped at the upper end.

The fluid-dynamic part of the analysis may be illustrated by results of the computer code YAQUIR (Fig. 2), where pressure profiles of the unwrapped downcomer are shown for the times 1, 4, 7 and 10 ms after blowdown initiation. At the blowdown nozzle and the lower plenum constant pressures (56 bar and 110 bar resp.) were assumed. The geometry corresponds to the HDR-blowdown facility described later in this paper.

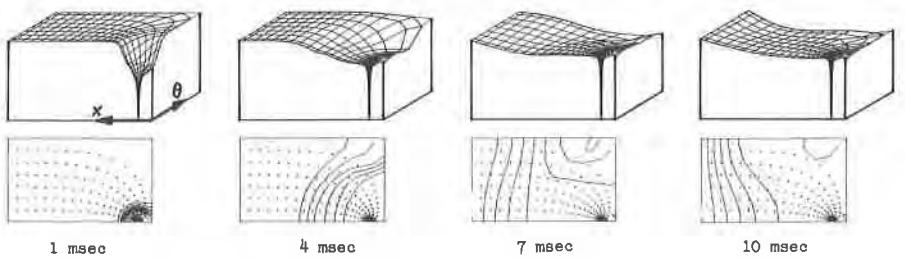


Fig. 2: Pressure Field in the Downcomer for an Idealized HDR-Blowdown at Different Times (x is Axial Direction, θ is Azimuthal Direction)

From Fig. 2 two major effects may be seen: The sharp pressure reduction in the neighbourhood of the nozzle is reduced considerably 4 ms after blowdown initiation, when the fluid

has been accelerated to its quasistationary velocity. The tilting of the axial pressure waves causes the global bending leading to the beam type of core barrel deformations. Corresponding results for the structural dynamic part of the analysis have been obtained with the computer code CYLDY2. Details are presented in [1].

2. Need for Safety Analysis Including Dynamic Fluid-Structural Coupling

Neglecting the structural dynamic feedback on the fluid dynamics may considerably affect the resulting core barrel stresses and deformations. This can be seen as follows: Assume that the core barrel is surrounded inside and outside by an infinite fluid field. An expansion wave with a pressure step of Δp may traverse this fluid field. Neglecting completely the core barrel stiffness and assuming that the material density reduces to the value of the fluid density, then no wave reflection will occur and the maximum strain ε_{max} can easily be calculated by

$$\varepsilon_{max} = \Delta p / (\varrho \frac{\partial p}{\partial \varrho})$$

Here $1/(\varrho \frac{\partial p}{\partial \varrho})$ is the compressibility of the fluid which in the case of a LWR-blowdown amounts to about 10^{-9} m^2/N. Introducing a pressure step of Δp = 20 bar, which may represent an upper bound value for the core barrel loading, the maximum strain is

$$\varepsilon_{max} = 0.2\,\%$$

Now taking into account the stiffness and the real material density of the core barrel one can expect that at least the average values of the strains are lower than 0.2 %, whatever the thickness of the core barrel might be.

In the state-of-the-art analysis methods, however, the calculated strains increase as the wall thickness of the core barrel decreases. For zero stiffness the calculated strains would become infinite which is in contradiction to the above conservative estimate for ε_{max}. Based on these considerations one can conclude that at least for more severe conditions with strains reaching the 0.2 %-value (note, that about the same value applies to the yield point) the state-of-the-art analysis methods are excessively conservativ. However, no information is given about the degree of conservatism and the resulting safety margins.

On the other hand, safety analysis in structural mechanics requires knowledge about the safety margins. Usually the safety margins are introduced in terms of admissible stresses and strains which are considerably lower than the corresponding ultimate values. Depending on the conditions (normal conditions, upset conditions,...) the commonly used safety factors in terms of stresses are at least between 2 and 3. In terms of strains the usual safety factor is much bigger. However, the difference between admissible values and the failure thresholds does not only apply to the inevitable uncertainties of the ultimate values. It also takes into account uncertainties in loading, geometry and - last not least - shortcomings of the analysis methods. This implies knowledge about the influences of load and geometry deviations on stresses and - if applicable - on strains. Otherwise the spectrum of loading and geometry variations (tolerance fields) which are within the failure thresholds could not be determined.

In the case of core barrel stresses due to a postulated blowdown the above procedure cannot be applied immediately for two reasons. First, the state-of-the-art approach does not

provide information about the degree of conservatism, which means poor knowledge about the safety margins in terms of stresses and strains. Secondly, as indicated by the above estimate of the maximum strain the influence of variations in loading and geometry on stresses and strains is relatively complex and not known. To overcome these problems, the theoretical blowdown models must be improved in order to obtain best estimate computer codes rather than purely conservative assessments. Furthermore the computer codes must be able to investigate blowdown events with varying load and geometry parameters such, that the resulting stresses and strains approach the failure threshold. However, as found by the simple model of wave propagation, the uncoupled state-of-the-art method becomes invalid for strains approaching the 0.2 %-value. Consequently more accurate theoretical models which especially take into account the phenomenon of dynamic fluid structural coupling are required.

3. Design of the HDR Experiments for Simulation of the Coupled Fluid Structural Dynamics in Case of a PWR-Blowdown

For verification of computer codes describing the coupled fluid structural dynamics in case of a blowdown, experiments are necessary satisfying the following - in some ways contradictory - requirements:

- The experimental model should be a well scaled mock up of real PWR's.
- However, certain deviations to reach more severe conditions, i.e., to emphasize the effect of dynamic fluid structural coupling are desired.
- Details which are not essential for the overall process but create difficulties in result interpretation should be omitted.

For this purpose the former HDR-reactor is available as an experimental facility. (The HDR-reactor was operated for a short time as a test reactor with nuclear superheating of steam. It was shut down after fuel element failure.) Fig. 3 shows a comparison between the HDR-facility, prepared for the blowdown experiments, and a typical PWR-reactor. One can see, that the overall size of the experimental facility comes close to reality (first requirement of chapter 2). This allows for a rich instrumentation with negligible influences of the measurement equipment on mass, stiffness and flow area of the experimental mock-up. Furthermore the time scales are about the same as in reality which is important for a good time resolution of the dynamic behavior (time scale is roughly proportional to length scale). Details of the test instrumentation including about 170 fast transducers, as well as more informations on the experimental design are given in [2].

From Fig. 3 also some major differences between the experimental facility and reality may be seen. While the height of the HDR-vessel is about the same, the diameter is 3000 mm instead of 5000 mm and the blowdown nozzle (inlet nozzle) has a size of only 200 mm instead of 900 mm. Due to the relatively small blowdown nozzle considerable load reductions in comparison to a real blowdown event must be expected. With respect to the stresses in the core barrel these reductions are compensated by both, the smaller diameter and a smaller wall thickness of the core barrel. While the first quantity is essentially determined by the vessel diameter, the appropriate wall thickness was subjected to extensive considerations. On one hand irreversible core barrel deformations are not allowed since the same core barrel

has to be used for several tests. On the other hand, the deformation should be as big as possible in order to emphasize the effect of fluid structural coupling (note, that also according to the ASME-Boiler-Pressure Vessel Code, Section III, plastic deformations are allowed). Therefore not a core barrel wall thickness of 30 mm, obtained from conservative state-of-the-art computer codes, was chosen. Rather the degree of conservatism was estimated and hence a wall thickness of 23 mm was taken. Now, it is expected that the full elastic load carrying capacity will be utilized.

A second point of intentional deviation from typical PWR design is the core barrel clamping. An almost rigid upper core barrel flange has been used having a residual flexibility of less than 0.2 mm when the full blowdown load is applied. Consequently only small clamping moments enter the core barrel and allow for relatively high overall stresses and deformations. This again emphasizes the effect of fluid structural coupling. At the same time a relatively rigid core barrel clamping facilitates the interpretation of the experimental results. The exact simulation of a typical PWR-core barrel clamping, however, with certain allowances for axial flange movements would require core barrel models which are strongly non-linear because of impacts between flange and pressure vessel.

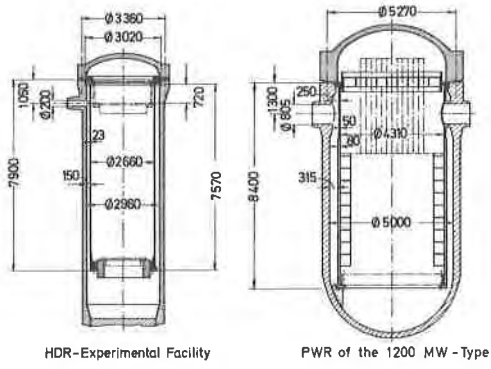


Fig. 3: Comparison between the HDR-Facility and a Typical 1200 MW PWR

Similar to real reactors, a lower flange stiffens the core barrel in such a way that its lower end deformations are restricted to rigid body movements. However, in contrast to reality, core barrel internals such as fuel mock-ups etc. are not present. To obtain dynamic core barrel properties which are not too far from those of a typical PWR, the lower core barrel flange carries a mass ring which has a mass of about 10 000 kg. This ring roughly simulates the inertia effect of that portion of a PWR-core which is supported by the lower core barrel flange. As a consequence of this design some minor interaction effects between the core structure and the surrounding fluid are not properly modeled. Nevertheless, with respect to the goal of code verification this is a reasonable approach, since in the codes a detailed modelling of the core structure is also impossible.

With respect to the fluid- and thermodynamics in case of a blowdown two pressure differences govern the blowdown behavior: The difference between the initial reactor pressure and the saturation pressure in the downcomer determines the height of the expansion wave propagating through the reactor. The difference between the initial reactor pressure and the saturation pressure inside the core barrel determines the first blowdown phase of a very steep overall pressure reduction (subcooled phase). Both differences are simulated properly by the HDR-test facility. Tests with higher pressure differences (second requirement of chapter 2) can be done. A proper simulation of the flow field before blowdown initiation, however, was found to be unessential. Therefore in the HDR-test facility the temperature difference between inside core barrel and downcomer can be established by a special heating and cooling system which is completely different from usual reactor cooling systems. The heat source is outside the reactor vessel and the power is much lower than in similar PWR's. It was found that for a stable flow pattern the hot water must enter the vessel in the upper plenum while the cold water must enter at the lower plenum. The mixed water must be removed from the top end of the downcomer. Flow velocities are as low as a few mm/sec and cm/sec inside and outside the barrel respectively. Calculations show that across the core barrel a temperature difference up to 50 K can be achieved.

4. Computer Codes in Coupled Fluid Structural Dynamics

The HDR-blowdown experiments will be used for both: Verification of state-of-the-art blowdown computer codes, and verification of advanced computer codes in coupled fluid structural dynamics. In this paper we will concentrate on three advanced computer codes right now under development at the Institut für Reaktorentwicklung:

a) Coupling of an existing finite difference code for two-dimensional compressible fluid flow (modified YAQUI [3]) with a code for shell dynamics based on modal superposition [4].
   This coupled code named STRUYA will be applied to the dynamic system consisting of core barrel and downcomer. Within each time increment the fluid as well as the structural dynamic problem is treated independently except for the iteration of the pressure field. Details of the method and first results with a simple one-parameter structural model for the core barrel are presented in [1]. It is a considerable advantage of the above approach, that one may use the whole spectrum of existing computer codes in fluid as well as structural dynamics as subsystems. Concerning the computer times, however, the necessity for large numbers of time or iteration steps in order to reach stability, turns out to be a major drawback.

b) Simultaneous integration of the fluid and structural equations by explicitly accounting for the interface conditions suited for the given problem.
   The concentration on a restricted class of coupled problems leads to considerable advantages concerning the computer effort. The code FLUX treats the complete three-dimensional problem including non-axisymmetric pressure distributions, flow velocities, deformations, etc. of downcomer, core barrel, lower and upper plenum and the inner region. However, the geometry must be (approximately) axisymmetric which is the case with the blowdown problem

under investigation. The other simplifying assumptions such as a one-phase potential flow do not represent major restrictions since fluid structural coupling is a dominant effect only for almost incompressible fluids and the viscous forces are small in comparison to the inertia forces. The coupling between fluid and structure is performed on the mathematical equation level. The governing Poisson-equation for the fluid dynamics is solved using fast Fourier transform (FFT), cyclic reduction and the capacitance-matrix technique. In its first version, FLUX 1, the code is restricted to incompressible fluid. A central part of FLUX 1 computes the virtual fluid mass and solves the resulting eigenproblem describing the coupled fluid structural dynamics. The structural dynamics part makes use of the CYLDY2 model [4]. More details will be given in chapter 5.

c) Modification of mass and stiffness matrices of finite element models for shell dynamics by reducing the 3D incompressible fluid problem to 2D with the boundary integral equation method.

Similar to the approach under b) the coupling between fluid and structure is performed on the mathematical equation level which allows for simultaneous integration of the fluid and structural equations by explicitely accounting for the interface condition. The method is in principle applicable to three-dimensional problems with any geometry. The fluid compressibility is neglected. In some applications, low fluid compressibilities may be approximated by additional artificial structural flexibilities. The structure is assumed to consist of thin shells which at the same time represent the interface surface between fluid and structure. Concerning the structural dynamics a relation between pressures, accelerations and displacements of the two-dimensional interface is given using mass and stiffness matrices which are provided by the well known finite elemente technique. Concerning the fluid dynamics, the derivation of an equivalent relation between accelerations and pressures of the two-dimensional interface requires the reduction of the three-dimensional fluid problem to a two-dimensional form where the unknowns occur only at the boundaries. Here, this is done by the boundary integral equation method [5, 6] which is the essential difference with respect to b). Once both relations are available, an eigenvalue problem can be obtained similar to the eigenvalue problem describing the structural dynamics without fluid coupling. Only the matrices involved undergo same changes and become non-symmetrical.

The above method will rather be applied to problems with full three-dimensional geometries like the stress analysis for the pressure supression system of a BWR in case of a blowdown, than to the stress analysis of the PWR vessel internals in case of a blowdown.

5. Details of the Code FLUX and First Results

The first running version, FLUX 1, assumes in addition to one-phase potential flow an incompressible fluid. This is, of course, a rather incisive approximation, which will be dropped in FLUX 2 (under development). It has been found [7], however, that the overall flow characteristics can rather well be predicted even under the above assumption which, on the other hand, considerably reduces the amount of numerical analysis.

Numerically, the flow calculation for transient potential flow requires the solution of a Poisson-type equation

$$\text{div grad } p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = q \qquad (1)$$

for time dependent boundary conditions and varying values of q (c = velocity of sound, $1/c^2 = 0$ for incompressible fluid). This equation can be solved in a rectangular geometry, as shown in Fig. 4, using fast Poisson-solvers. We use cosine-transform (employing FFT) with respect to the azimuthal variation. For each cosine-mode a finite difference approximation to eq. (1) is set up in r-z-coordinates. The resulting system of equations, which is linear under the present assumptions, is solved for each of the rectangular parts (1 to 5 in Fig. 4) using the cyclic-reduction algorithm POISSXP [8, 9, 10]. Here, it is important that this code is applicable to an arbitrary number of grid points (not restricted to powers of two as the original Buneman version of this algorithm [10]). The boundary and interface conditions between the adjacent rectangles are satisfied by means of the capacity matrix technique [8, 10]. (For a total of 16 500 grid points this equation is solved within 10 seconds on an IBM 370/168).

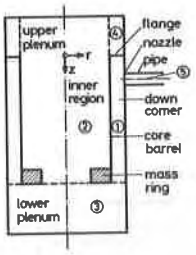


Fig. 4: Idealized Reactor Vessel Geometry Considered in FLUX

FLUX 1 consists of three parts. The first one computes the transient pressure load on the core barrel for rigid structure. Here, the time dependence can be expressed analytically [7] as $p(\underline{x},t) = p_o(\underline{x}) + (p_\infty(\underline{x}) - p_o(\underline{x}))\cdot\tanh^2(t/\tau)$. ($p_o$ and p_∞ are the pressure at times zero and infinity, resp.) The constant τ is of the order 10 msec for the HDR. In this case the cosine modes are coupled due to the boundary condition at the nozzle inlet. The second part computes the virtual mass matrix $\underline{\underline{F}}$ [11]. Here, each cosine mode can be treated independently because - assuming the flow rate out of the nozzle to be given as computed in part 1 - the boundary condition at the nozzle is the same as elsewhere at the vessel wall and because of the orthogonality of the cosine functions and because of neglecting nonlinear terms as required for a linear eigenanalysis. Each column of the matrix $\underline{\underline{F}}$ is equal to the modal pressure load resulting from a unit modal acceleration of the structure mode corresponding to this column. Then the program solves the eigenvalue problem

$$\underline{\underline{S}}\,\underline{x} - \omega^2\,(\underline{\underline{F}}+\underline{\underline{M}})\,\underline{x} = \underline{0}$$

defined by the stiffness matrix $\underline{\underline{S}}$ and the sum of the structural mass matrix $\underline{\underline{M}}$ and the virtual fluid mass matrix $\underline{\underline{F}}$. Here $\underline{\underline{M}}$, $\underline{\underline{S}}$ and the modal deformations are taken from CYLDY2 [4]. Moreover, the second part of FLUX 1 transforms the pressure loading which resulted from the first part into modal forces. A principal axis transformation [12], which separates the coupled dynamic equations, closes this part. The third part integrates the dynamical equation, which now has the form $\ddot{w}_j + 2\,d_j\,\omega_j\,\dot{w}_j + \omega_j^2\,w_j = p_j(t)$ for each principal axis j, for given initial values $w_j(t=0)$ and $\dot{w}_j(t=0)$. (The damping coefficients d_j are computed assuming wall friction laws for the viscous forces between the fluid and the structure; the resultant values of d_j are typically less than 10^{-5} and can be neglected therefore.) From the results the actual deformations of the structure are computed.

Fig. 5 shows some of the resulting eigenfrequencies $(\omega/2\pi)$ and eigenoscillations of the core barrel in vacuum (pure CYLDY2-result) and water. Shown are the first three (n = 0,1,2) cosine modes and the eigendeformations w(z) corresponding to the lowest eigenfrequencies for each azimuthal mode. We observe a drastic decrease of the eigenfrequency when the water inertia is included. The form of the eigensolutions is nearly the same in water and vacuum except for the zeroth mode. Here the lowest eigenfrequency is connected with an oscillation which causes a maximum amount of water to be accelerated. This is the case for a longwave eigendeformation with large deflection near the upper flange as shown in Fig. 5.

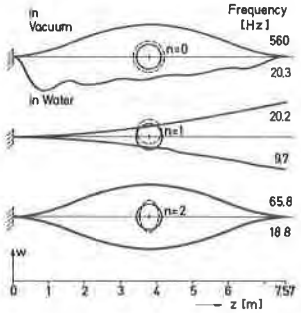


Fig. 5: Mode Shapes for the Lowest Eigenfrequencies of the Three Lowest Cosine Modes in Vacuum and Water

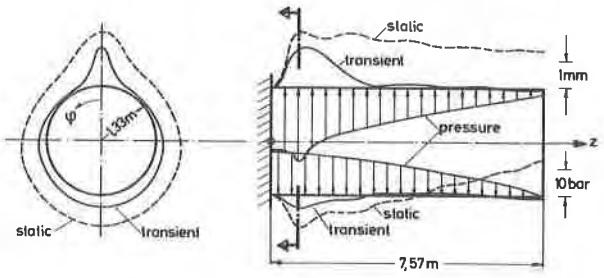
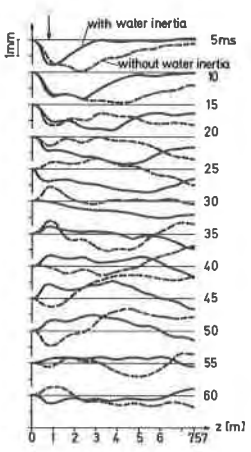


Fig. 6: Pressure Distribution, Transient Deformation (snapshot at 5 ms) and Static Deformations of the Core Barrel

Fig. 6 shows the core barrel and the pressure load for time $t \approx 0$. The pressure has been computed with constant boundary values 110 bar in the upper plenum and 60 bar at the pipe outlet (length 0.2 m). The pressure load decreases with time and becomes very small for large times except near the nozzle [7]. Also shown are the corresponding static deformations and the resulting transient deformations for t = 5 ms. All these results are obtained for 9 azimuthal and 10 axial structural modes. Some of the observed spurious oscillations are expected to decrease for larger number of modes. The deformations are typically of the order 1 mm. They are smaller in the transient computation than in the static one - as expected; however, the curvature and thus the local stresses (not yet evaluated) might well be larger in the transient case. Smaller pressure loads and deformations result for longer pipes [7].

Fig. 7 shows the deformed meridian of the core barrel adjacent to the nozzle for a sequence of times. The full curves are for the core barrel in water. The dashed curves show the response of the barrel to the same loading but without accounting for the inertia of the water with respect to the oscillations ($\underline{F}$ is set to zero in part 2). This figure demonstrates the importance of the structure-fluid interaction. It should be noted, however, that these computations are approximative as they do not account for a change of the loading due to structural deformations. Interestingly, the results show some wave propagation in the core barrel (wave speed about 200 m/s) and the lower end seems to behave like a whip (see Fig. 7 for t = 35 msec).



The results shown above are computed with a total of 7 minutes computing time, which shows that 3D analysis must not be expensive. Whether the assumption of incompressibility can be justified will be decided by the compressible analysis which is under preparation.

Fig. 7: Transient Core Barrel Deformations for the Meridian Close to the Blowdown Nozzle with and without Water Inertia Effects for Different Times

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